CHAPTER 4

Pulse Code Modulation Standards

Acronyms **4-iii**

Chapter 4. Pulse Code Modulation Standards **4-1**

4.1 General **4-1**
4.2 Class Distinctions and Bit-Oriented Characteristics **4-1**

4.2.1 Class I and Class II Distinctions 4-1
4.2.2 Bit-Oriented Definitions and Requirements 4-2
4.2.3 Bit Clocking Definitions and Requirements 4-4

4.3 Fixed Formats **4-5**

4.3.1 Word-Oriented Definitions and Requirements 4-5
4.3.2 Frame Structure 4-6
4.3.3 Cyclic Redundancy Check (Class II) 4-8

4.4 Format Change (Class II) **4-9**

4.4.1 Frame Format Identification 4-9
4.4.2 Format Change Implementation Methods 4-9

4.5 Asynchronous Embedded Format (Class II) **4-9**
4.6 Tagged Data Format (Class II) **4-9**

4.6.1 Alternating Tag and Data 4-9
4.6.2 Bus Data, MIL-STD 1553 4-10
4.6.3 Bus Data, ARINC 429 4-10

4.7 Time Words **4-10**
4.8 Asynchronous Data Merge (Class II) **4-12**

4.8.1 PCM Data Word Format 4-12
4.8.2 Insertion Process 4-12

Appendix 4-A. Additional Information and Recommendations **A-1**

A.1. Bit Rate Versus Receiver Intermediate-Frequency Bandwidth **A-1**

A.2. Recommended PCM Synchronization Patterns **A-2**

A.3. Spectral and BEP Comparisons for NRZ and Bi-phase **A-3**

A.4. PCM Frame Structure Examples **A-4**

Appendix 4-B. Citations **B-1**

List of Figures

Figure 4-1. PCM Code Definitions 4-3
Figure 4-2. PCM Clock Definitions 4-4
Figure 4-3. PCM Frame Structure 4-6

Figure 4-4. 16-Bit Standardized Time Word Format 4-10
Figure 4-5. Time Word Insertion Into 12-Bit PCM Word Size..... 4-11
Figure 4-6. Asynchronous Word Structure..... 4-12
Figure A-1. BEP vs. IF SNR in Bandwidth = Bit Rage for NRZ-L PCM/FM A-1
Figure A-2. Spectral Densities of Random NRZ and Biϕ Codes A-3
Figure A-3. Theoretical BEP Performance for Various Baseband PCM Signaling Techniques (Perfect Bit Synchronization Assumed) A-4

List of Tables

Table 4-1. Overhead Truth Table 4-13
Table A-1. Optimum Frame Synchronization Patterns for PCM Telemetry A-2
Table A-2. Minor Frame Maximum Length, N Words or B Bits A-5
Table A-3. Major Frame Length = Minor Frame Maximum Length Multiplied by Z A-6
Table A-4. Major Frame Length = Minor Frame Maximum Length Multiplied by Z A-7

Acronyms

BCD	binary coded decimal
BEP	bit error probability
Biϕ	bi-phase
Biϕ-L	bi-phase-level
Biϕ-M	bi-phase-mark
Biϕ-S	bi-phase-space
CRC	cyclic redundancy check
dB	decibel
FFI	frame format identifier
FM	frequency modulation
IF	intermediate-frequency
lsb	least significant bit
Mbps	megabit per second
msb	most significant bit
NRZ-L	non-return-to-zero-level
NRZ-M	non-return-to-zero-mark
NRZ-S	non-return-to-zero-space
PCM	pulse code modulation
RF	radio frequency
RNRZ-L	randomized non-return-to-zero-level
SFID	subframe identifier
SNR	signal-to-noise ratio

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CHAPTER 4

Pulse Code Modulation Standards

4.1 General

Pulse code modulation (PCM) data are transmitted as a serial bit stream of binary-coded time-division multiplexed words. When PCM is transmitted, premodulation filtering shall be used to confine the radiated radio frequency (RF) spectrum in accordance with Chapter 2 Appendix 2-A. These standards define pulse train structure and system design characteristics for the implementation of PCM telemetry formats. Additional information and recommendations are provided in Appendix 4-A and in RCC 119-06.[1]

4.2 Class Distinctions and Bit-Oriented Characteristics

The PCM formats are divided into two classes for reference. Serial bit stream characteristics are described below prior to frame and word oriented definitions.

4.2.1 Class I and Class II Distinctions

Two classes of PCM formats are covered in this chapter: the basic, simpler types are Class I, and the more complex applications are Class II. The use of any Class II technique requires concurrence of the range involved. All formats with characteristics described in these standards are Class I except those identified as Class II. The following are examples of Class II characteristics.

a. Bit rates greater than 10 megabits per second (Mbps) (Subsection 4.2.2 item c).

b. Word lengths in excess of 32 bits (Subsection 4.3.1 item a).

c. Fragmented words (Subsection 4.3.1 item b).

d. More than 8192 bits or 1024 words per minor frame (Subsection 4.3.2 item a(1)).

e. Uneven spacing, not within the definition of subcommutation (Subsection 4.3.2 item c) or supercommutation (Subsection 4.3.2 item d).

f. Format changes (Section 4.4).

g. Asynchronous embedded formats (Paragraph 4.5).

h. Tagged data formats (Section 4.6).

i. Formats with data content other than unsigned straight binary, discretes, or complement arithmetic representation for negative numbers such as floating point variables, binary-coded decimal, and gain-and-value.

j. Asynchronous data transmission (Section 4.8).

k. Merger of multiple format types (such as those specified in Chapter 8).

[1] Range Commanders Council. *Telemetry Applications Handbook*. RCC 119-06. May 2006. May be superseded by update. Retrieved 4 June 2015. Available at http://www.wsmr.army.mil/RCCsite/Documents/119-06_Telemetry_Applications_Handbook/.

l. Use of a cyclic redundancy check (CRC) word (Subsection 4.3.3).

m. Use of fill bits (Subsection 4.3.2 item a).

n. Use of non-fixed frame synchronization patterns.

NOTE	The use of fixed frame formats has been a common practice but does not fit all requirements. A verification of range capabilities should be made prior to incorporation of Class II features into a telemetry system.

4.2.2 Bit-Oriented Definitions and Requirements

Definitions and requirements relating to serial PCM bit streams are described next.

a. Binary Bit Representation. The following code conventions for representing serial binary ones and zeros are the only permissible representations. Graphic and written descriptions of these conventions are shown in Figure 4-1. Only one convention shall be used within a single PCM bit stream. If randomized non-return-to-zero-level (RNRZ-L) is transmitted, it shall use the 15-bit regeneration pattern as described in Annex A.2.

(1) Non-return-to-zero-level (NRZ-L)

(2) Non-return-to-zero-mark (NRZ-M)

(3) Non-return-to-zero-space (NRZ-S)

(4) Bi-phase-level (Biϕ-L)

(5) Bi-phase-mark (Biϕ-M)

(6) Bi-phase-space (Biϕ-S)

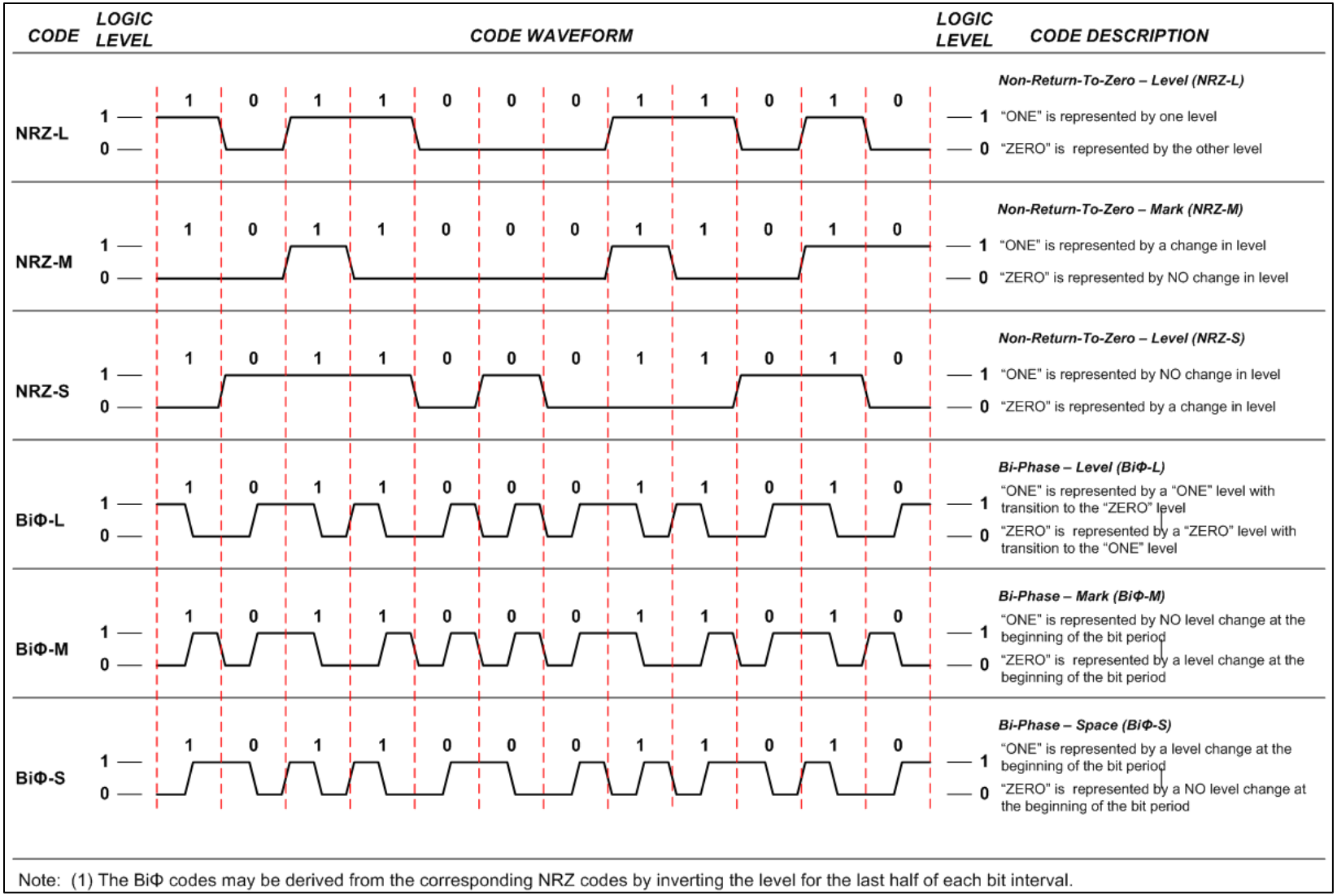

Figure 4-1. PCM Code Definitions

b. Serial Bit Stream Transitions. The transmitted or recorded bit stream shall be continuous and shall contain sufficient transitions to ensure bit acquisition and continued bit synchronization, taking into account the binary representation chosen. See the recommendation in Section A.3.

c. Bit Rate. The RF and recording limits, defined in Chapter 2 and Chapter 6, should be considered when determining maximum bit rates. The minimum bit rate shall be 10 bits per second. Bit rates greater than 10 Mbps are Class II.

d. Bit Rate Accuracy and Stability. During any period of desired data, the bit rate shall not differ from the specified nominal bit rate by more than 0.1 percent of the nominal rate.

e. Bit Jitter. The bit jitter shall not exceed ±0.l of a bit interval referenced to the expected transition time with no jitter. The expected transition time shall be based on the measured average bit period as determined during the immediately preceding 1000 bits.

4.2.3 Bit Clocking Definitions and Requirements

Clock phase is defined in relationship to data transition. Graphic and written descriptions of following conventions are shown in Figure 4-2.

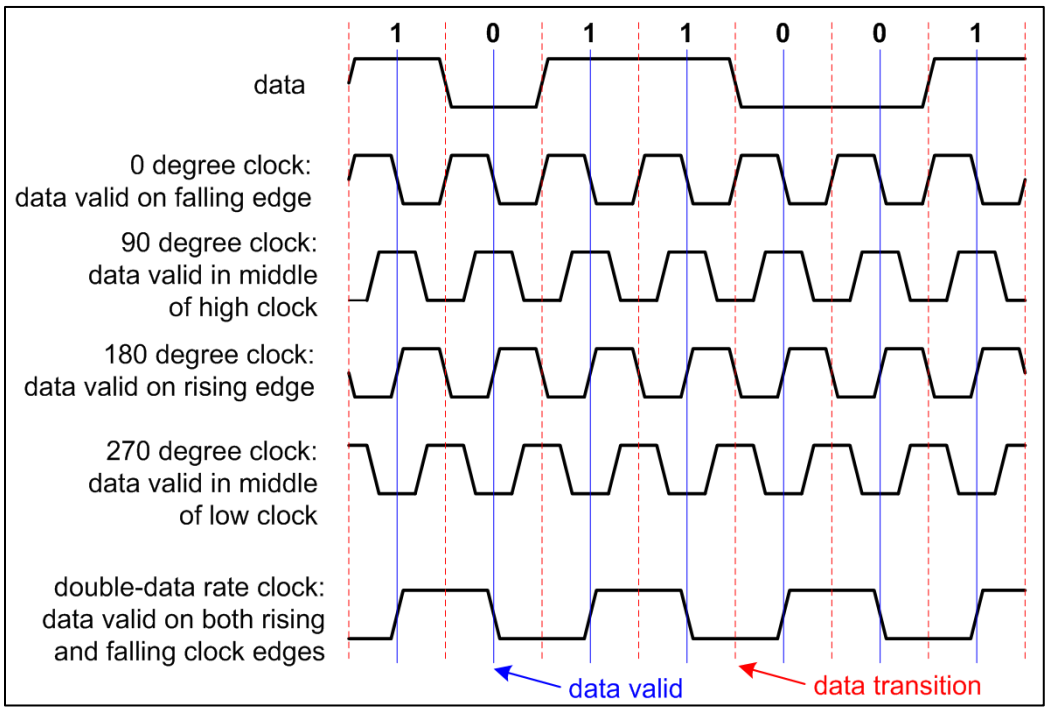

Figure 4-2. PCM Clock Definitions

a. 0° clock. Data transitions on the rising edge of the clock. Data is valid on the falling edge of the clock.

a. 90° clock. Data transitions in the middle of clock low. Data is valid in the middle of clock high.

b. 180° clock. Data transitions on the falling edge of the clock. Data is valid on the rising edge of the clock.

c. 270° clock. Data transitions in the middle of clock high. Data is valid in the middle of clock low.

d. Double-data rate clock. Also known as half clock. Data transitions in the middle of both clock high and low. Data is valid on both rising and falling edge of clock.

4.3 Fixed Formats

Characteristics of fixed formats are described below. Fixed formats do not have changes during transmission with regard to frame structure, word length or location, commutation sequence, sample interval, or measurement list.

4.3.1 Word-Oriented Definitions and Requirements

The following definitions and requirements are addressed to word characteristics.

a. Word Length (Class I and II). Individual words may vary in length from 4 bits to not more than 32 bits in Class I and not more than 64 bits in Class II.

b. Fragmented Words (Class I and II). A fragmented word is defined as a word divided into no more than eight segments and placed in various locations within a minor frame. Locations need not be adjacent. For Class I, all word segments used to form a data word shall be constrained to the boundaries of a single minor frame. Class II may fragment across minor frames, though this is not recommended. Fragmented synchronization words are not allowed.

c. Bit Numbering. To provide consistent notation, the most significant bit (msb) in a word shall be numbered “one”. Less significant bits shall be numbered sequentially within the word.

d. Word Numbering. To provide consistent notation, the minor frame synchronization pattern word shall be numbered “zero” and the first word after the minor frame synchronization pattern shall be numbered “one” (see Figure 4-3). Each subsequent word shall be sequentially numbered within the minor frame. Numbering within a subframe (see Subsection 4.3.2 item c(1)) shall be “one” for the word in the same minor frame as the initial counter value for subframe synchronization and sequentially thereafter. Notations of W and S shall mean the W word position in the minor frame and S word position in the subframe.

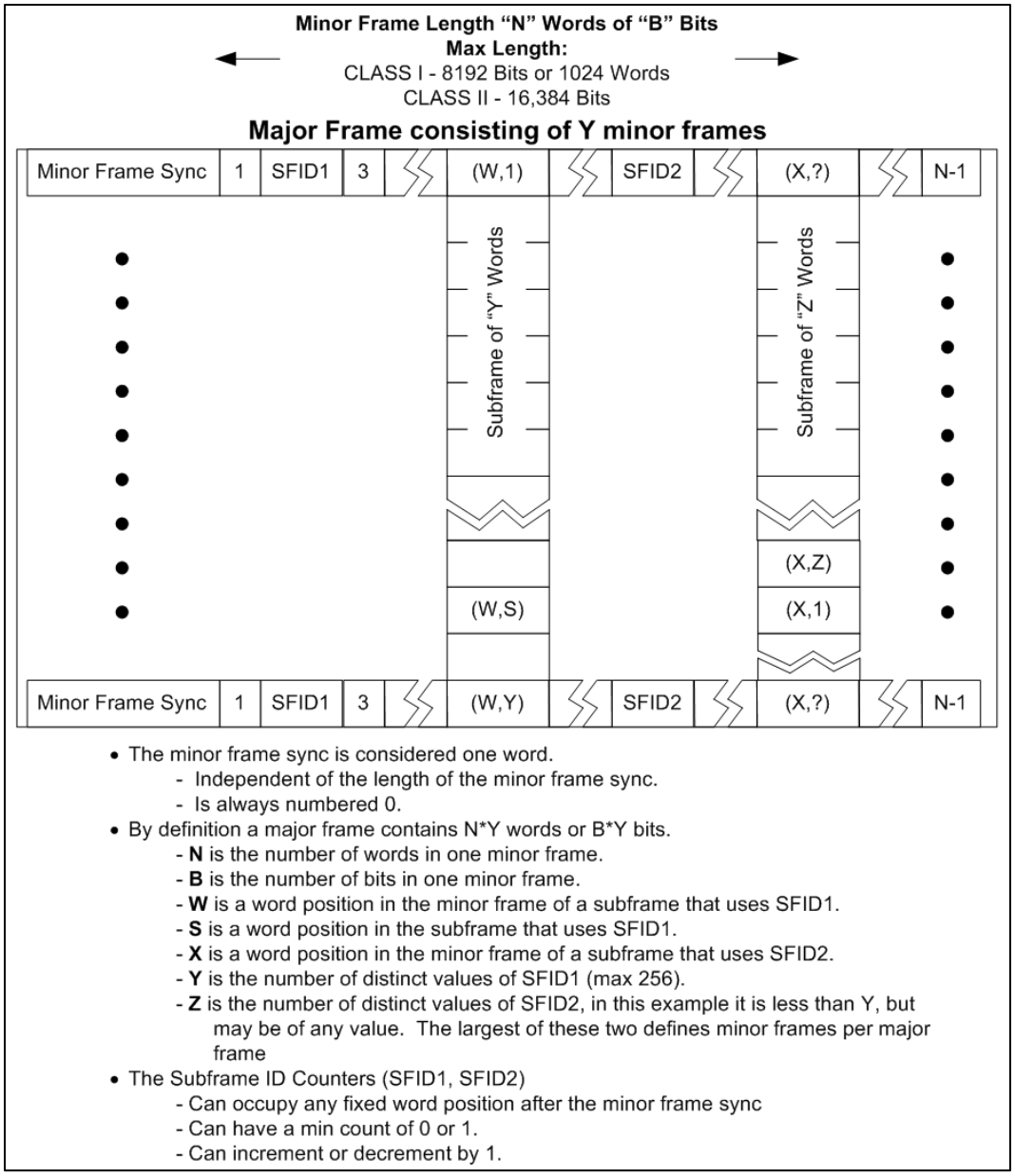

Figure 4-3. PCM Frame Structure

4.3.2 Frame Structure

The PCM data shall be formatted into fixed length frames as defined in these sections regarding frame structure and in Figure 4-3. Frames shall contain a fixed number of equal duration bit intervals.

a. Minor Frame. The minor frame is defined as the data structure in time sequence from the beginning of a minor frame synchronization pattern to the beginning of the next minor frame synchronization pattern. Certain Class II PCM systems may insert a variable number of fill bits between the end of one minor frame and the synchronization pattern of the next minor frame. When this is done, these filler bits are not considered to be a part of either minor frame.

(1) Minor Frame Length (Class I and II). The minor frame length is the number of bit intervals from the beginning of the frame synchronization pattern to the beginning of the next synchronization pattern. The maximum length of a minor frame shall exceed neither 8192 bits nor 1024 words in Class I and shall not exceed 16384 bits in Class II. If fill bits are inserted, they are not to be used in the calculation of the minor frame length.

(2) Minor Frame Composition. The minor frame shall contain the minor frame synchronization pattern, data words, and subframe synchronization words, if used. Words of different length may be multiplexed in a single minor frame. The length of a word in any identified word position within a minor frame shall be constant. Other words such as frame format identifiers (FFIs) may be needed within Class II formats (see Section 4.4).

(3) Minor Frame Synchronization. The minor frame synchronization information shall consist of a fixed digital word not longer than 33 consecutive bits and not shorter than 16 bits. The minor frame synchronization pattern is always considered as one word, regardless of its length. Recommended synchronization patterns are given in Table A-1. Class II formats may use an alternating complement synchronization pattern that complements after each minor frame.

(4) Transmitted Frame Counter. The frame counter provides a natural binary count corresponding to the minor frame number in which the frame count word appears. It is recommended that such a counter be included in all minor frames whether Class I or Class II and is especially desirable in Class II formats to assist with data processing. The frame counter should be of nominal format word length and reset to start up-counting again after reaching maximum value. In formats where subcommutation is present, the subframe identifier (SFID) counter may serve as the frame counter.

(5) Bit Numbering in a Minor Frame. To provide consistent notation, the first bit in a minor frame (the first bit in the sync pattern) shall be numbered “one”. Each subsequent bit shall be sequentially numbered within the minor frame. This is used for CRC.

b. Major Frame. A major frame contains the number of minor frames required to include one occurrence of every word in the format. See Figure 4-3.

(1) Major Frame Length. Major frame length is defined as minor frame length (N words or B bits) multiplied by the number of minor frames (Z) in the major frame. The maximum number of minor frames per major frame shall not exceed 256.

(2) Minor Frame Numbering. To provide consistent notation, the first minor frame in a major frame shall be numbered “one”. Each subsequent minor frame shall be numbered sequentially within the major frame.

c. Subcommutation. Subcommutation is defined as a sampling of parameters at submultiple rates (1/D) of the minor frame rate where the depth of a subframe, D, is an integer in the range of 2 to Z.

(1) Subframe. Subframe is defined as one cycle of the parameters from a subcommutated minor frame word position. The depth, D, of a subframe is the number of minor frames in one cycle before repetition.

(2) Subframe Synchronization Method. The standard method for subframe synchronization is to use a SFID counter, a binary counter that counts sequentially up or down at the minor frame rate. Typically, only one SFID counter is used in a PCM format; however, more than one counter may be used if needed. This paragraph assumes the use of one SFID counter. The SFID counter shall be located in a fixed position in each and every minor frame. The counter should start with the minimum counter value when counting up or the maximum counter value when counting down. The counter should also be left or right justified in a word position. The start of a major frame shall coincide with the initial count for the deepest subframe.

(3) SFID Counter Location. The SFID counter should be placed in the minor frame prior to any subcommutated parameters. Subcommutated parameters that occur in the minor frame prior to the SFID counter are undefined.

d. Supercommutation. Supercommutation is defined as time-division-multiplex sampling at a rate that is a multiple of the minor frame rate. Supercommutation (on a minor frame) provides multiple samples of the same parameter in each minor frame. *Supercommutation on a subframe* is defined as time-division-multiplex sampling at a rate that is a multiple of the subframe rate and provides multiple samples of the same parameter within a subframe. For Class I, supercommutated samples shall be evenly spaced. For Class II, supercommutated samples should be as evenly spaced as practical.

4.3.3 Cyclic Redundancy Check (Class II)

A CRC is an error-detecting code commonly used in digital networks and storage devices. It can detect strings of bit errors that are of the length of the CRC check word. If a CRC check word is to be used, it should be inserted at the end of each minor frame and occupy the same location in each minor frame. It shall not occupy any bits from the frame sync pattern. It shall occupy contiguous bits, but may cross word boundaries. The CRC check word shall always be inserted msb first.

The CRC shall be calculated in bit-transmit order. The maximum length of bits to be checked shall be the length of one minor frame, but the bits being checked may span two minor frames. Minor frame fill bits shall not be used as part of a CRC calculation. The CRC calculation shall not use pre-inversion, post-inversion, reversed bit ordering, unusual starting value, or final XOR. Since ground station software typically runs in a general purpose computer, the decoding of the CRC will usually be done in software. Therefore, only a subset of 16 and 32 bit CRCs shall be supported. The supported CRC polynomials are as follows:

CRC-16-ANSI: $x^{16} + x^{15} + x^{2} + 1$

CRC-16-CCITT: $x^{16} + x^{12} + x^{5} + 1$

CRC-32: $x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} + x^{10} + x^{8} + x^{7} + x^{5} + x^{4} + x^{2} + x + 1$

4.4 Format Change (Class II)

Format change is defined as change with regard to frame structure, word length or location, commutation sequence, sample interval, or change in measurement list. Format changes shall occur only on minor frame boundaries. Bit synchronization shall be maintained and fill bits used instead of intentional dead periods. Format changes are inherently disruptive to test data processing; fixed format methods are preferred. Format change methods shall conform to the characteristics described in the following sections.

4.4.1 Frame Format Identification

An FFI is a word that shall uniquely identify a single format. In formats where change is required, the FFI shall be placed in every minor frame. The format identifier shall be the same length as (or multiples of) the most common word length in the format and shall occur in a fixed position in the minor frame. The FFI shall identify the format applicable to the current minor frame. Frame synchronization pattern, FFI location, bit rate, and binary bit representation code shall not be changed. The FFI shall be constructed such that a single bit error cannot produce another valid FFI. The number of unique formats indicated shall not exceed 16.

4.4.2 Format Change Implementation Methods

The following subparagraphs describe format change implementation methods.

a. Measurement List Change. This method of format change consists of a modification in data content only and not format structure.

b. Format Structure Change. Defined as a format change where there is a departure in frame structure and not just data content.

4.5 Asynchronous Embedded Format (Class II)

An asynchronous embedded format is defined as a secondary data stream asynchronously embedded into a host major frame in a manner that does not allow predicting the location of embedded synchronization information based only on host format timing. It is recommended that the embedded frame segments be inserted as an integral number of words in every host minor frame, so that in the combined format, specific word positions in the host minor frame are dedicated to the embedded asynchronous format; however, placing the asynchronous embedded format only in selected host minor frames is permitted. It is also recommended that no more than two asynchronous embedded formats be inserted in a host major frame, but more than two are permitted.

4.6 Tagged Data Format (Class II)

A tagged data format is defined as a fixed frame length format having no applicable subframe or major frame definitions and characterized as a stream of data words, or blocks of words, with associated identifiers (tags). These formats consist of frame synchronization patterns, identifiers, data words, and fill words as required.

4.6.1 Alternating Tag and Data

This tagged data format consists of frames containing tag words alternating in time sequence with data words or blocks of words identified by the tags.

4.6.2 Bus Data, MIL-STD 1553

The preferred method of telemetering MIL-STD 1553 information is for the information to be restructured to conform to Class I methods. If not restructured, telemetered MIL-STD 1553 data shall conform to Chapter 8. This data format is described in Military Standard 1553[2].

4.6.3 Bus Data, ARINC 429

The preferred method of telemetering ARINC information is for the information to be restructured to conform to Class I methods. If not restructured, telemetered ARINC 429 data shall be consistent with the specification of ARINC 429 bus data, as implemented in Chapter 8. This data format is described in Aeronautical Radio, Inc. 429[3].

4.7 Time Words

The following paragraphs describe the formatting of time words within a PCM stream. A 16-bit standardized time word format and a method to insert time words into PCM word sizes other than 16-bits are described.

In 16-bit standardized time word format, there shall be three words dedicated to providing timing information. These words are designated high order time, low order time, and microsecond time. High and low order time words shall be binary or binary coded decimal (BCD) weighted, and microsecond words shall be binary weighted. Time word construction examples are shown in Figure 4-4 and Figure 4-5.

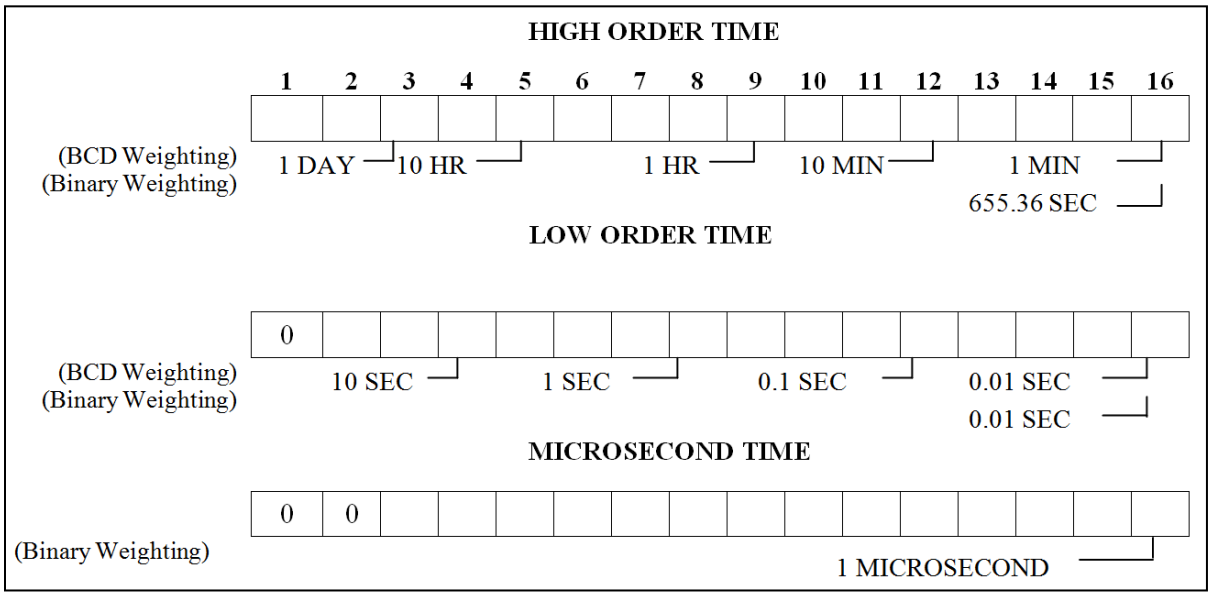

Figure 4-4. 16-Bit Standardized Time Word Format

[2] Department of Defense. *Aircraft Internal Time Division Command/Response Multiplex Data Bus*. MIL-STD-1553B. 21 September 1978. May be superseded by update. Retrieved 4 June 2015. Available at http://quicksearch.dla.mil/basic_profile.cfm?ident_number=36973&method=basic.

[3] Aeronautical Radio, Inc. *Mark 33 Digital Information Transfer System (DITS)*. ARINC 429. Annapolis: ARINC, 1995.

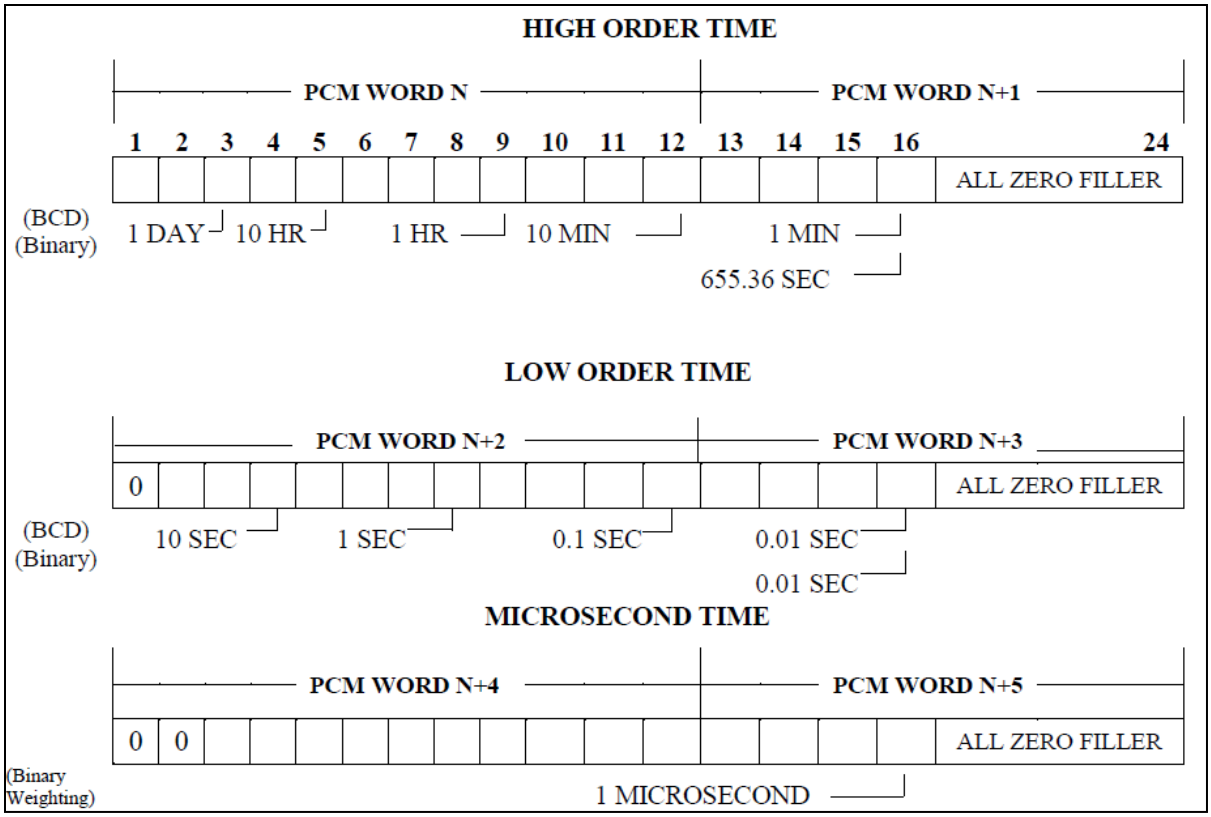

Figure 4-5. Time Word Insertion Into 12-Bit PCM Word Size

The microsecond time word shall have a resolution of 1 microsecond; that is, the least significant bit (lsb), bit 16, has a value of 0.000001 second. This word shall increment until it attains a value of 10 milliseconds at which time it will reset to zero. Thus the maximum value of the counter is 9999 (decimal).

The low order time word shall have a resolution of 10 milliseconds; that is, the lsb, bit 16, of the low order time word shall have a value of 0.01 second.

The high order time word shall have a resolution of 655.36 seconds when binary weighted; that is, the lsb, bit 16, has a value of 655.36 seconds. When BCD weighted, the lsb, bit 16, of the high order time word shall have a value of one minute. For BCD, the days field shall contain the three least significant bits of the BCD Julian date.

It is recommended that high, low, and microsecond time words precede the first data word in the minor frame. The time word order shall be high order time word, followed by low order time word, followed by microsecond time word. Microsecond time words may be used to tag individual data words, but care shall be taken that high order and low order time words be inserted at a rate necessary to resolve time ambiguities.

Time word insertion into PCM word sizes other than 16 bits shall be as follows: high order, low order, and microsecond time words shall be inserted into PCM words with time word bits occupying contiguous bit locations in the PCM word. The time word shall occupy contiguous PCM data words until the time word is contained in the PCM stream. If the time word size is not an integer multiple of the PCM word size and there are unused bits in the PCM word, the remaining unused bits in the last PCM word that contains the time word shall be fill

bits with value 0. Figure 4-5 illustrates the insertion of time words into a PCM stream with word size of 12 bits.

4.8 Asynchronous Data Merge (Class II)

Asynchronous data is defined as an external sequential data stream (consisting of data bits, associated overhead, and optional parity, all at an autonomous update rate) that is a candidate for insertion into a primary or "host" PCM format. Common examples are RS-232 serial and IEEE-488 parallel messages. This section does not apply to secondary PCM formats that are to be embedded as described in Paragraph 4.5. Merger shall comply with Subsection 4.2.2.

Each source of merged data shall use fixed word positions in the host format. It is recommended that the merged data be inserted as an integral number of words in every host minor frame, so that in the combined format, specific word positions in the host minor frame are dedicated to the merged data format; however, placing the merged data format only in selected host minor frames is permitted. It is also recommended that no more than two merged data formats be inserted in a host major frame, but more than two are permitted. The following conventions are recommended, but variations are allowed.

4.8.1 PCM Data Word Format

Figure 4-6 illustrates the host PCM format word containing a merged asynchronous data word and associated overhead, which is referred to as an *asynchronous word structure*. The data may be inserted in any length PCM word that will accommodate the required bits. Asynchronous data shall not be placed in fragmented words. Multiple host PCM format words, if used, shall be contiguous.

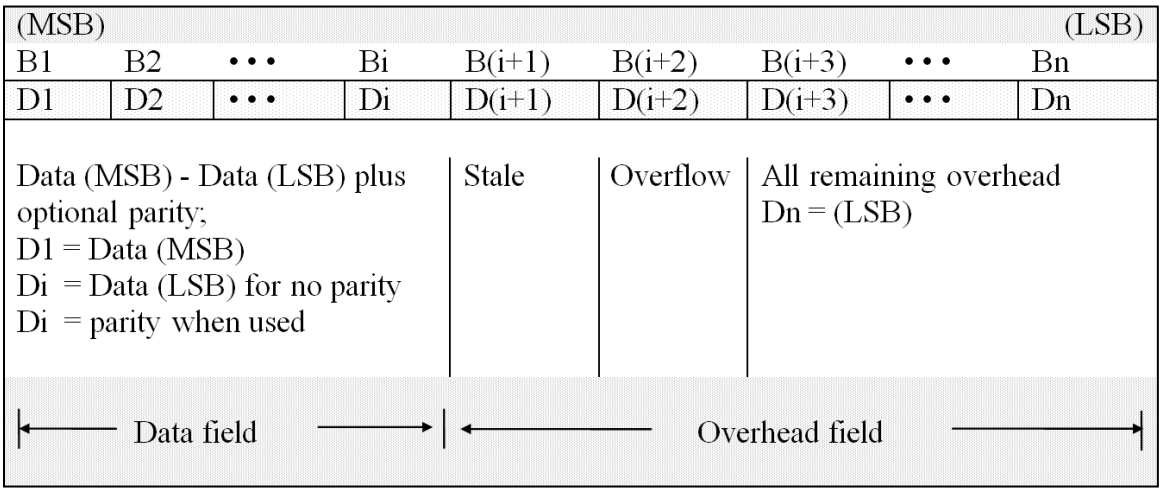

Figure 4-6. Asynchronous Word Structure

4.8.2 Insertion Process

The asynchronous word structure shall contain the information from the asynchronous message partitioned into two fields, data and overhead, as shown in Figure 4-6. The asynchronous message is inserted into the asynchronous word structure with the following bit orientations. The most significant data bit (msb) through least significant data bit (lsb) and parity

(if used) of the message are denoted as D1 (msb) through Di and will be inserted into structure bits B1 (msb) through Bi. The next two structure bits, B(i+1) and B(i+2) are reserved for the stale and overflow flags generated by the host encoder. All remaining overhead (message and host encoder generated) D(i+3) through Dn (lsb), will be inserted into structure bits B(i+3) through Bn (lsb).

a. Transmission Overhead. All transmission overhead not required for data reconstruction shall be removed.

b. Parity Bit. Transmission of a parity bit is optional. If it is transmitted, it shall be at the end of the data field (see Figure 4-6) adjacent to the lsb of the data.

c. Data Bits. The data bits shall be inserted into the PCM word with the msb of the asynchronous data aligned with the msb of the PCM word.

d. Stale Data Bit. A *stale data bit* flag shall be generated each time a new data value is inserted into the PCM stream. The flag shall be transmitted with the associated data. The flag bit shall be placed in the next less significant bit location following the lsb of the data. If new data is not ready for transmission by the time the PCM word must be sent again, either the old data or alternating one/zero fill shall be sent and the flag set. Stale data shall be indicated by a binary "one" (see Table 4-1).

Table 4-1. Overhead Truth Table

Stale Bit	Overflow Bit	
0	0	Fresh Data
0	1	Data Overflow
1	0	Stale Data
1	1	User Defined

e. Overflow Bit. An *overflow bit* flag shall be generated to indicate an abnormal condition in which data may be lost. The overflow bit shall be placed in the next less significant data bit location following the stale bit flag. An overflow bit at a binary "one" indicates that a data discontinuity exists between the current data word and the previous data word (see Table 4-1 above).

f. Insertion Rate. The asynchronous word structure shall be inserted into the host PCM word at a rate to avoid data loss in the PCM stream.

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APPENDIX 4-A

Additional Information and Recommendations

A.1. Bit Rate Versus Receiver Intermediate-Frequency Bandwidth

The following subparagraphs contain information about selection of receiver intermediate-frequency (IF) bandwidths. Additional information is contained in RCC document 119-06.

The standard receiver IF bandwidth values are listed in Chapter 2, Table 2-1. Not all bandwidths are available on all receivers or at all test ranges. Additional bandwidths may be available at some test ranges. The IF bandwidth, for data receivers, should typically be selected so that 90 to 99 percent of the transmitted power spectrum is within the receiver 3-decibel (dB) bandwidth.

For reference purposes, in a well-designed PCM/frequency modulation (FM) system (NRZ-L data code) with peak deviation equal to 0.35 times the bit rate and an IF bandwidth (3 dB) equal to the bit rate, a receiver IF signal-to-noise ratio (SNR) of approximately 13 dB will result in a bit error probability (BEP) of 10^{-6}. A 1-dB change in this SNR will result in approximately an order of magnitude change in the BEP. The relationship between BEP and IF SNR in a bandwidth equal to the bit rate is illustrated in Figure A-1 for IF bandwidths equal to the bit rate and 1.5 times the bit rate. An approximate expression for the BEP is:

$$\text{BEP} = 0.5\, e^{(k \cdot \text{SNR})} \qquad \text{Eqn. A-1}$$

where: $k \approx -0.7$ for IF bandwidth equal to bit rate
$k \approx -0.65$ for IF bandwidth equal to 1.2 times bit rate
$k \approx -0.55$ for IF bandwidth equal to 1.5 times bit rate
SNR = IF SNR•IF bandwidth/bit rate.

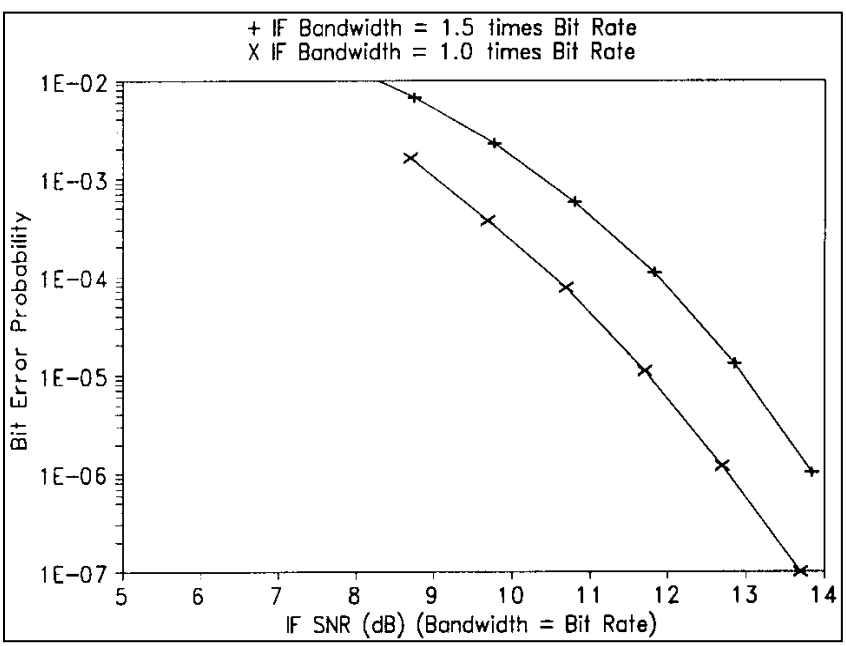

Figure A-1. BEP vs. IF SNR in Bandwidth = Bit Rage for NRZ-L PCM/FM

Other data codes and modulation techniques have different BEP versus SNR performance characteristics.

It is recommended that the maximum period between bit transitions be 64-bit intervals to ensure adequate bit synchronization.

A.2. Recommended PCM Synchronization Patterns

Table A-1 contains recommended frame synchronization patterns for general use in PCM telemetry. Patterns are shown in the preferred order of transmission with "111" being the first bit sequence transmitted. This order is independent of data being least-significant-bit or most-significant-bit aligned. The technique used in the determination of the patterns for lengths 16 through 30 was essentially that of the patterns of 2^n binary patterns off a given length, n, for that pattern with the smallest total probability of false synchronization over the entire pattern overlap portion of the ground station frame synchronization.[4] The patterns for lengths 31 through 33 were obtained from a second source.[5]

Table A-1. Optimum Frame Synchronization Patterns for PCM Telemetry

Pattern Length	Patterns										
16	111	010	111	001	000	0					
17	111	100	110	101	000	00					
18	111	100	110	101	000	000					
19	111	110	011	001	010	000	0				
20	111	011	011	110	001	000	00				
21	111	011	101	001	011	000	000				
22	111	100	110	110	101	000	000	0			
23	111	101	011	100	110	100	000	00			
24	111	110	101	111	001	100	100	000			
25	111	110	010	110	111	000	100	000	0		
26	111	110	100	110	101	100	110	000	00		
27	111	110	101	101	001	100	110	000	000		
28	111	101	011	110	010	110	011	000	000	0	
29	111	101	011	110	011	001	101	000	000	00	
30	111	110	101	111	001	100	110	100	000	000	
31	111	111	100	110	111	110	101	000	010	000	0
32	111	111	100	110	101	100	101	000	010	000	00
33	111	110	111	010	011	101	001	010	010	011	000

[4] A more detailed account of this investigation can be found in a paper by J. L. Maury, Jr. and J. Styles, "Development of Optimum Frame Synchronization Codes for Goddard Space Flight Center PCM Telemetry Standards." In *Proceedings of the National Telemetering Conference*, June 1964.

[5] The recommended synchronization patterns for lengths 31 through 33 are discussed more fully in a paper by E. R. Hill, "Techniques for Synchronizing Pulse-Code Modulated Telemetry." In *Proceedings of the National Telemetering Conference*, May 1963.

A.3. Spectral and BEP Comparisons for NRZ and Bi-phase[6]

Figure A-2 shows the power spectral densities of baseband NRZ and Biϕ codes with random data. These curves were calculated using the equations presented below. Figure A-3 presents the theoretical BEPs versus SNR for the level, mark, and space versions of baseband NRZ and Biϕ codes and also for RNRZ-L. The noise is assumed to be additive white Gaussian noise.

$$\textit{NRZ SPECTRAL DENSITY} \quad \alpha \quad \frac{\sin^2(\pi fT)}{(\pi fT)^2} \qquad \text{Eqn. A-2}$$

$$\textit{Bi}\phi \textit{ SPECTRAL DENSITY} \quad \alpha \quad \frac{\sin^4(\pi fT/2)}{(\pi fT/2)^2} \qquad \text{Eqn. A-3}$$

where T is the bit period.

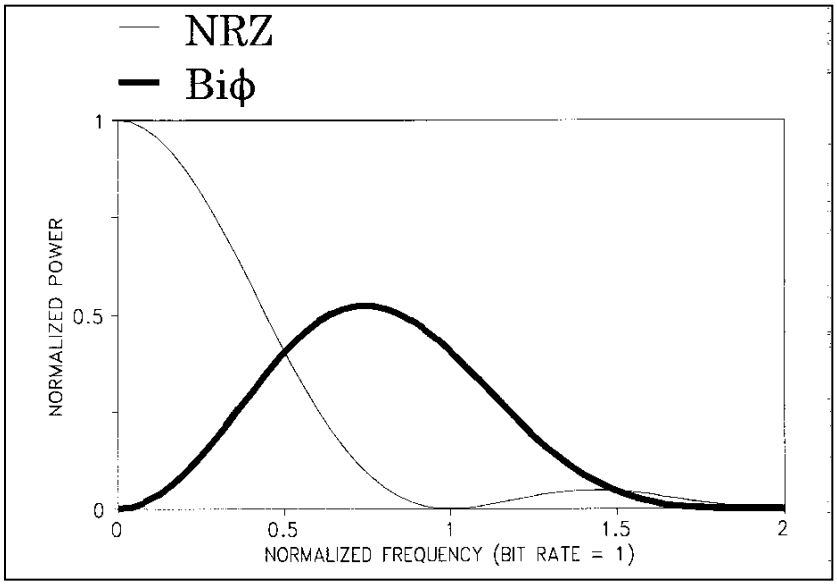

Figure A-2. Spectral Densities of Random NRZ and Biϕ Codes

[6] Material presented in paragraph 3.0 is taken from a study by W. C. Lindsey (University of Southern California), *Bit Synchronization System Performance Characterization, Modeling and Tradeoff Study*. AD-766974. Naval Missile Center Technical Publication. 4 September 1973. Retrieved 3 June 2015. Available at http://www.dtic.mil/cgi-bin/GetTRDoc?AD=AD0766794.

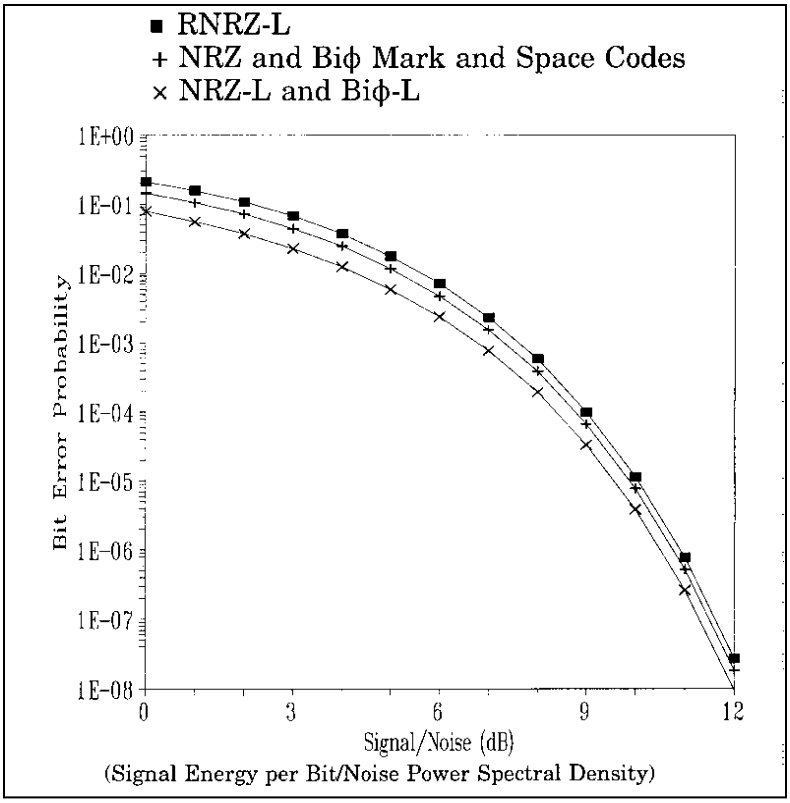

Figure A-3. Theoretical BEP Performance for Various Baseband PCM Signaling Techniques (Perfect Bit Synchronization Assumed)

A.4. PCM Frame Structure Examples

Table A-2, Table A-3, and Table A-4 show examples of allowable PCM frame structures. In each example, the minor frame sync pattern is counted as one word in the minor frame. The first word after the minor frame sync pattern is word 1. Table A-3 and Table A-4 show the preferred method of placing the SFID counter in the minor frame. The counter is placed before the parameters that are referenced to it.

Major frame length is as follows:

- Table A-2: Major frame length = minor frame maximum length.
- Table A-3: Major frame length = minor frame maximum length multiplied by Z.
- Table A-4: Major frame length = minor frame maximum length multiplied by Z.

Table A-2. Minor Frame Maximum Length, N Words or B Bits

Class I: Shall not exceed 8192 bits nor exceed 1024 words
Class II: 16 384 Bits

	Word 1	Word 2	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8	Word 9	Word 10	...	...	...	Word N-2	Word N-1
Minor Frame Sync Pattern	Param A0	Param A1	Param A2	Param A3	Param A4	Param A2	Param A5	Param A6	Param A2	Param A7	...	...	...	Param A2	Param A(X)

Parameters A0, A1, A3, A4, A5, A6, ... A(X) are sampled once each minor frame.
Parameter A2 is supercommutated on the minor frame.
The rate of A2 is equal to the number of samples multiplied by the minor frame rate.

Table A-3. Major Frame Length = Minor Frame Maximum Length Multiplied by Z

Minor Frame Maximum Length, N Words or B Bits

Class I shall not exceed 8192 bits nor exceed 1024 words. Class II: 16 384 bits.

	Word 1	Word 2	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8	Word 9	Word 10	• • •	Word N-2	Word N-1
Minor frame sync pattern	SFID= 1	FFI	Param A2	Param B1	Param A4	Param A2	Param A5	Param A6	Param A2	Param C1	• • •	Param A2	Param A(X)
	SFID= 2			Param B2						Param C2			
	SFID= 3			Param B3						Param C3			
	SFID= 4			Param B4						Param C4			
	SFID= 5			Param B2						Param C5			
	SFID= 6			Param B5						Param C6			
	SFID= 7			Param B6						Param C7			
	. .			. .	. .					. .			
	. .			Param B2						Param C(Z-1)			
Minor frame sync pattern	SFID =Z	FFI	Param A2	Param BZ	Param A4	Param A2	Param A5	Param A6	Param A2	Param CZ	• • •	Param A2	Param A(X)

The frame format identifier (word 2) is shown in the preferred position as the first word following the ID counter. Parameters B1, B3, B4, B5, . . . BZ, and C1, C2, C3, . . . CZ are sampled once each subframe, at 1/Z multiplied by the minor frame rate. Parameter B2 is supercommutated on the subframe and is sampled at less than the minor frame rate, but greater than the subframe rate.

Table A-4. Major Frame Length = Minor Frame Maximum Length Multiplied by Z

Minor Frame Maximum Length, N Words or B Bits

Class I shall not exceed 8192 bits or exceed 1024 words. Class II: 16 384 bits.

	Word 1	Word 2	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8	Word 9	Word 10	• • •	Word N-2	Word N-1
Minor frame sync pattern	SFID1 =1	FFI	Param A2	SFID2 =1	Param B1	Param A2	Param A5	Param E1	Param A2	Param C1	• • •	Param A2	Param A(X)
	SFID1 =2			SFID2 =2	Param B2			Param E2		Param C2			
	SFID1 =3			SFID2 =3	Param B3			Param E3		Param C3			
	SFID1 =4			SFID2 =4	Param B4			Param E4		Param C4			
	SFID1 =5			SFID2 =5	Param B2			Param E5		Param C5			
	SFID1 =6			. .	Param B5			. .		Param C6			
	SFID1 =7			SFID2 =D	Param B6			Param ED		Param C7			
	. .			. . .	. .	. .		. . .		. .			
	. .				Param B2					Param C(Z-1)			
Minor frame sync pattern	SFID1 =Z	FFI	Param A2	SFID2 =N	Param BZ	Param A2	Param A5	Param EN	Param A2	Param CZ	• • •	Param A2	Param A(X)

SFID1 and SFID2 and subframe counters.
SFID1 has a depth Z≤ 256; SFID2 has a depth D <Z. Z divided by D is not an integer.
Location of the B and C parameters are given by the minor frame word number and the SFID1 counter.
Location of the E parameters are given by the minor frame word number and the SFID2 counter.

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APPENDIX 4-B

Citations

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****** END OF CHAPTER 4 ******